

Background power subtraction in Ly α forest

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When measuring the one-dimensional power spectrum of the Ly α forest, it is common to measure the power spectrum in flux fluctuations red-ward of the Ly α emission of quasars and subtract this power from the measurements of the Ly α flux power spectrum. This removes excess power present in the Ly α forest which is believed to be dominated by metal absorption by the low-redshift metals uncorrelated with the neutral hydrogen absorbing in Ly α . In this brief report we note that, assuming the contaminants are additive in optical depth, the correction contains a second order term. We estimate the magnitude of this term for two currently published measurements of the 1D Ly α flux power spectrum and show that it is negligible for the current generation of measurements. However, future measurements will have to take this into account when errorbars improve by a factor of two or more.

I. INTRODUCTION

The Lyman- α forest measurements are becoming increasingly more accurate and to that end careful investigation of possible systematic effects is required. In this brief report we study the effect of background power fluctuations which contaminate the signal in the Ly α forest region.

Fluctuations in the Ly α forest region in the spectra of distant quasars, that is region between the rest Ly α and Ly β emission lines (with some buffer to immunize against proximity effects) is dominated by the Ly α absorption. However, metals in the inter-galactic medium will contaminate this signal coming from neutral hydrogen. There are several techniques to attack this important systematics. For the metal transitions which occur at wavelengths similar to the Ly α emission wavelength ($\lambda_\alpha = 1215.67\text{\AA}$) we can rely on the fact that the contaminant metals are closely tracing the dominant absorption by neutral hydrogen producing detectable “beating” in the power spectrum measurements. This has been demonstrated in [6, 7] for Si III and [4] for O VI. On the other hand it is relatively easy to remove contribution to absorption by metals with transitions $\lambda \gg \lambda_\alpha$. The most common way to do this is to study the the power spectrum of fluctuations redward of the Ly α emission in the spectra of quasars. Since gas behind the quasars cannot absorb quasar light, this power is often termed as background power – the power spectrum in absence of signal – and subtracted from the measured flux power spectrum.¹ It is believed that majority of this

signal is coming from a mixture of metal absorptions by a much lower redshift ($z < 1.5$) intergalactic medium. Since this gas is uncorrelated with the neutral hydrogen, it was commonly assumed that the two power spectra are uncorrelated and that a simple subtraction is sufficient. However, this signal adds to the total optical depth experienced by the quasar’s photons, which leads to a second order effect, which we discuss in this work. We will show that this effect is negligible for the present generation of one-dimensional flux power spectra measurements, but that it will likely become important for the final BOSS ([1, 3]) analysis, eBOSS ([9]) and DESI ([5]) experiments.

II. EFFECT OF CONTAMINANTS

For our analysis, we assume that observed flux in the relevant parts of quasar spectra is given by

$$f^q(\lambda_i) = C^q(\lambda_r) \times \begin{cases} e^{-\tau_\alpha(z_i) - \tau_c(z_i)} & \text{in forest region} \\ e^{-\tau_c(z_i)} & \text{in background region} \end{cases}, \quad (1)$$

where $C^q(\lambda_r)$ is the continuum of the quasar (results in this paper do not depend on the modeling of this quantity) and τ_α and τ_z are the optical depth associated with signal and contamination respectively. We write the absorptions as

$$e^{-\tau_\alpha(z_i)} = \bar{F}_\alpha(z_i)(1 + \delta_\alpha(\lambda_i)) \quad (2)$$

$$e^{-\tau_c(z_i)} = \bar{F}_c(z_i)(1 + \delta_c(\lambda_i)) \quad (3)$$

where \bar{F} is mean absorptions and δ are the corresponding fluctuations for the two components. Here we have

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¹ Note that for a given observed wavelength λ_o , there are quasars at somewhat larger redshift $1 + z > \lambda_o/\lambda_\alpha$ for which the wavelength is subject to both Ly α and contaminant absorptions and other quasars at somewhat lower redshifts $1 + z < \lambda_o/\lambda_\alpha$ for

which the same wavelength is absorbed only by the contaminant. Therefore one is subtracting statistically the same component, but observed in different quasars.

written δ_c as fluctuations due to low-redshift metals, but fluctuations due to continuum errors would have exactly the same form (i.e. be multiplicative). The forest region of the spectrum is the region of the forest blue-ward of Ly α emission, typically between rest frame wavelengths of 1050Å and 1185Å. Different authors have defined different background regions where absorption by metals is measured but all regions share the same qualities of having being as close as possible redward of Ly α emission and have smooth continuum without large emission lines (see [2, 6, 7]).

Faced with the real quasar spectra, it is impossible to distinguish between various absorbers and the best one can hope to do is to model the quasar flux as [2, 6-8]

$$f^q(\lambda_i) = C^q(\lambda_r) \times \begin{cases} \bar{F}_T(z_i)(1 + \delta_T(\lambda_i)) & \text{in forest region} \\ \bar{F}_c(z_i)(1 + \delta_c(\lambda_i)) & \text{in redward region} \end{cases}, \quad (4)$$

Inside the forest region the total fluctuation field can be written as

$$1 + \delta_T(\lambda) = (1 + \delta_\alpha(\lambda))(1 + \delta_c(\lambda)). \quad (5)$$

We see that in addition to the usual linear relation used in previous works there is also a second order (quadratic) term in the total absorption flux fluctuation field in the forest

$$\delta_T(\lambda) = \delta_\alpha(\lambda) + \delta_c(\lambda) + \delta_\alpha(\lambda)\delta_c(\lambda). \quad (6)$$

The correlation function of this quantity is given by

$$\langle \delta_T(\lambda)\delta_T(\lambda') \rangle = \xi_T(\lambda, \lambda') = \xi_\alpha(\lambda, \lambda') + \xi_c(\lambda, \lambda') + \xi_\alpha(\lambda, \lambda')\xi_c(\lambda, \lambda') \quad (7)$$

Here we have assumed that δ_α and δ_c are completely uncorrelated fields. This is justified by the fact that the metals doing the contaminant absorption are sitting in a gas that is $> 1000h^{-1}\text{Mpc}$ away from hydrogen gas.

Fourier transforming, we find that power spectra are given by

$$P_T(k) = P_\alpha(k) + P_c(k) + (P_\alpha \star P_c)(k), \quad (8)$$

where \star stands for suitably normalized convolution.

On the quasar's red-side, there is no forest and therefore the measured power spectrum is simply $P_c(k)$. The point of this short note is that when a corrected power spectrum is calculated, the second order correction does not cancel

$$P_{\text{std.correction}}(k) = P_T(k) - P_c(k) = P_\alpha(k)(P_\alpha \star P_c)(k), \quad (9)$$

Therefore, to recover the sign power spectrum P_α it is not sufficient to simply subtract the contaminant power spectrum from the total power spectrum. In configuration space

$$\xi_\alpha(x) = \frac{\xi_T(x) - \xi_c(x)}{1 + \xi_c(x)}, \quad (10)$$

which gives

$$P_\alpha(k) = P_T(k) - P_c(k) - \Delta P(k), \quad (11)$$

where

$$\Delta P(k) = \int_{-\infty}^{\infty} dk' [P_T(k') - P_c(k')] W_k(k - k'), \quad (12)$$

and W_K is just the Fourier transform of a real space window function

$$W(x) = \frac{\xi_c(x)}{1 + \xi_c(x)}, \quad (13)$$

There are two interesting limits to these equations. First, if $\xi_c(x)$ is small compared to other quantities, we see that $W(k) \sim P_c(k)$, leading to

$$\Delta P(k) = (P_T \star P_c)(k) \quad (14)$$

(in effect approximating $P_\alpha(k)$ with $P_T(k)$ in Eq. 8). Second, when $P_c(x)$ is white, we see that

$$\Delta P(k) = \frac{\sigma_c^2 \sigma_\alpha^2}{2\pi}, \quad (15)$$

where sigma are the variances (i.e. zero lag correlators) of the α and c fields. We see that in that limit, the correction is purely white too.

In order to properly account for this effect, one would need to take it into account in the quadratic estimator used to measure the power spectrum (and likely perform the measurements of background and forest power jointly). However, to get a rough estimate, one can take measurements of the power spectra, Fourier transform those measurements to the configuration space, perform correction and transform back. We do this for two published results in the next section.

III. ESTIMATING THE SIZE OF THE EFFECT

To evaluate the correction from Eq. 12 we have used FFT algorithms to first compute the corresponding ξ_c and ξ_α and then to compute the inverse as given by Eq. 11. We did this for two published 1D power spectra [6, 7], which conveniently provided both the total power measured in the Ly α forest region as well as background power measured redward of the Ly α emission line. To deal with different binning schemes and finite coverage of k -space, we have first resampled the power spectra onto a finer k -space grid and given sufficient zero padding on both sides until results converged. We have also checked that the treating the power spectrum bins as either flat bandpower bins or linearly interpolating between bin centers made negligible difference.

In Figure 1 we plot the quantities P_T , P_m and ΔP on the same plot for three representative redshift bins. This plot shows that the correction is small, three orders

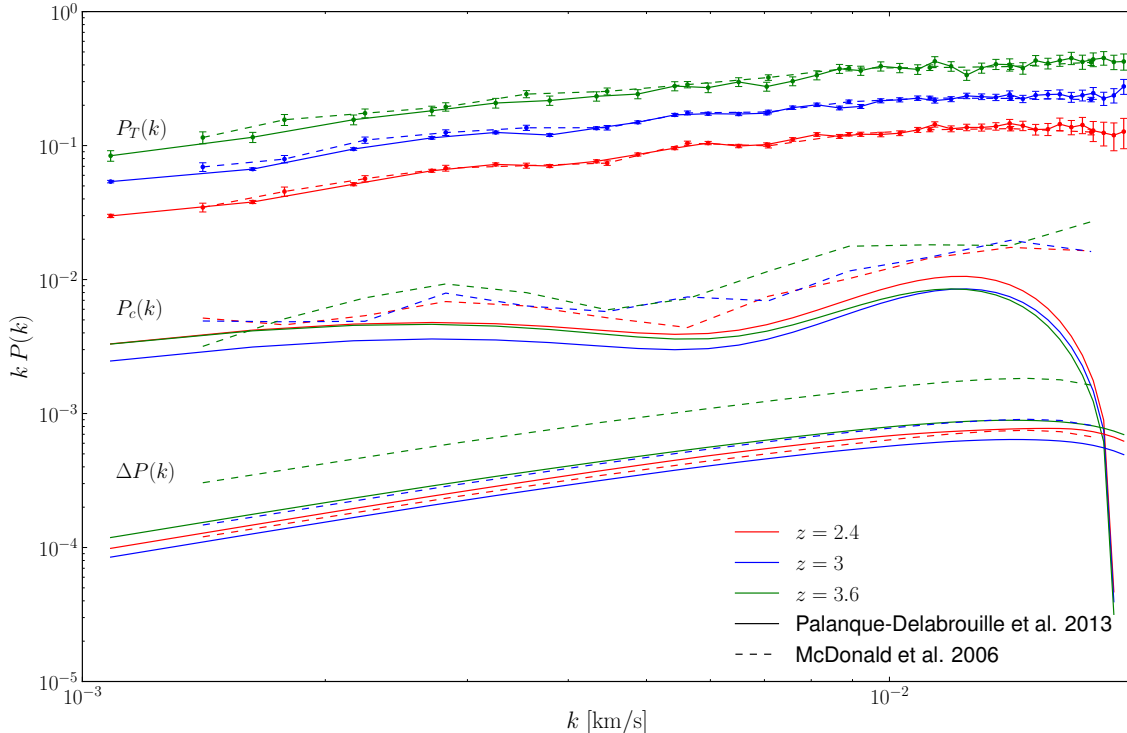


Figure 1. Total power spectrum, contaminant power spectrum and second order correction for 3 redshifts. Different colors correspond to different redshift bins, while different line-styles correspond to different analyses of the power spectra as denoted in the legend. See text for further discussion.

of magnitude smaller than the power spectrum and an order of magnitude smaller than the background power spectrum. The full lines show the analysis by [7] and the dashed lines show the first analysis by [6].

Note that due to small errorbars the correction is not as negligible as one might naively expect. In the Figure 2 we show the correction relative to the power spectra error estimates (both statistical and systematic). We see that for the current generation of power spectra measurements, the 2nd order correction is not yet important (around 10% of the current errors at redshift range $z = 3 - 4$). The implied change in χ^2 for previous works is ~ 1 for [6] (over 12 k bins and 11 redshift bins) and ~ 2 for [7] (at 35 k -bins and 12 redshift bins). This confirms that the size of the effect is probably negligible when compared to the current errorbars, but not by a large margin.

IV. CONCLUSIONS

In this brief report we have shown that multiplicative contaminations in the Lyman- α forest, such as those arising from continuum fluctuations and low redshift metals cannot be simply subtracted by measuring them outside

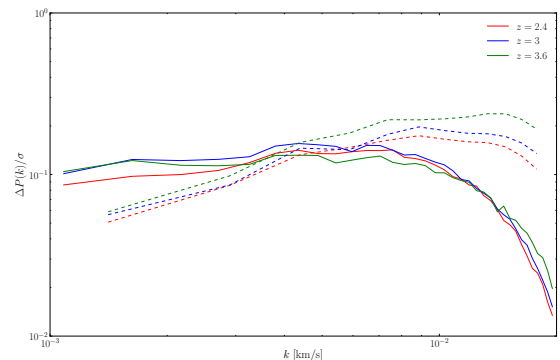


Figure 2. Correction with respect to the errors using the same color scheme as in Figure 1.

the forest region, but instead produce higher-order correction. This is typically small and indeed it does not matter for the current generation of the 1D power spectrum measurements.

The measurement of [7] has used approximately 14 thousands high signal-to-noise BOSS quasars, producing an effect of $\Delta\chi^2 \sim 2$. The full survey will contain ap-

proximately 160 thousand quasars and eBOSS and DESI experiments will likely increase the number of quasars to well over 600 thousand. This signal to noise is hence likely to increase by a factor of at least a few, bringing the expected size of the effect well into realm where correction will have to be applied.

Finally, we note that the correction mixes up small scales and large scales. While we can reliably say that small scale background power is likely coming from low-

redshift metals, we cannot say the same for the large-scale power in the background region. Some of the power on those scales will be associated with the continuum fluctuations, but these are now estimated at *a wrong part of the rest-frame spectrum*. For simple power subtraction this does not matter, but since the second order correction mixes scales, this set a fundamental limitations on how well one can perform this correction. We do not deal with this question in this brief report, but undoubtedly new techniques will arrive that will attack these issues.

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